Role of nucleon resonance excitation in ϕ meson photoproduction

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The resonance effects are investigated in the ϕ meson photoproduction near threshold through a quark model approach with an effective Lagrangian. The diffractive contribution is consistently estimated by the t-channel Pomeron exchange. Another non-diffractive process, t-channel π^0 exchange is also included. The numerical result shows that the Pomeron exchange plays dominant role in the ϕ meson photoproduction, while the cross sections of the non-diffractive processes, i.e., s- and u-channel excitations, and t-channel π^0 exchange, are quite small. In the polarization observables, we find that large asymmetries are produced in the backward direction by the interferences from the s- and u-channel resonances, while in the forward direction, only very small asymmetries are generated. Meanwhile, we find that the effects from the π^0 exchange are generally negligible.

1   Introduction

A well established feature in the ϕ meson photoproduction at low momentum transfer and high energies is that the diffractive scattering governs the reaction mechanism [1]. With the advent of the new high intensity beam facilities, like JLAB, ELSA, GRAAL, SPring-8, the study of this field in both low energy ($E_\gamma \sim 2$ GeV) and/or high momentum transfer ($-t \geq 1$ (GeV/c)^2) becomes possible. In these regimes, deviations, i.e. non-diffractive reactions, from the pure diffractive phenomena are expected, which should show up, especially in polarization observables. In this work, our purpose is to investigate the role played by the non-diffractive resonances in the ϕ meson photoproduction near threshold.

To reach this purpose, the first step must be to describe the diffractive phenomena in consistence with the experimental dat, i.e. to reproduce the energy-independent feature of the cross sections in $\gamma p \rightarrow \phi p$ at high energy regions, based on which the non-diffractive cross sections can be reasonably estimated. In this work, we introduce a t-channel Pomeron exchange model [2,3,4,5] to account for the diffractive phenomena in $\gamma p \rightarrow \phi p$ at high energies. In this model, the Pomeron is treated as a $C = +1$ isoscalar photon.

At present time, there is no systematic investigation of the role played by the resonances in the ϕ meson photoproduction. In fact, at hadronic level, the unknown $\phi N N^*$ couplings have been the barrier to go further to include the

resonances since one has to introduce at least one parameter for each $\phi N N^*$ coupling vertex, therefore, a large number of parameters will appear in the theory. On this point, the quark model approach shows great advantages: in the exact $SU(6) \otimes O(3)$ symmetry limit, the quark-vector-meson interactions can be described by the effective Lagrangian with only two parameters[6,7].

The contribution from π^0 exchange in $\gamma p \to \phi p$ is quite negligible in comparison with not only the Pomeron exchange in the small $|t|$ region, but also the resonance contributions in the large $|t|$ region though in some polarization observables the interference between the *natural parity* Pomeron exchange and the *unnatural parity* π^0 exchange produces sizable asymmetries.

We do not include the amplitude for the η exchange in this work, since although the ϕ meson has larger decay branching ratio for $\phi \to \eta\gamma$ than for $\phi \to \pi^0\gamma$, a recent analysis[8] of the η photoproduction shows that $g_{\eta NN}$ is smaller than $g_{\pi NN}$ by roughly a factor of 7, which leads to negligible effects due to the η exchange in the ϕ production.

The rest part of this work is arranged as follows. In section 2, a brief introduction is given to the formalism of the model. In section 3, the numerical results for the cross sections and the polarization observables are presented. Discussion and conclusion are given in section 4.

2   The model

2.1   s- and u-channel resonance excitations

We first introduce the quark model approach with effective Lagrangian to the s- and u-channel resonance contributions in $\gamma p \to \phi p$. The quark-vector-meson coupling is described by the effective Lagrangian:

$$L_{eff} = \overline{\psi}(a\gamma_\mu + \frac{ib\sigma_{\mu\nu}q^\nu}{2m_q})\phi_m^\mu\psi, \qquad (1)$$

where the quark field ψ can be u, d, or s for the light-quark baryon system. ϕ_m^μ represents the vector meson field for the light vector mesons (ω, ρ, K^* and ϕ). The 3-quark baryon system is described by the NRCQM in the $SU(6) \otimes O(3)$ symmetry limit in this calculation. The vector meson is treated as an elementary point-like particle which couples to the constituent quark through the effective interaction. a and b are the two parameters introduced in the s- and u-channel.

At tree level, the transition amplitude from the effective Lagrangian can be expressed as the contributions from the s-, u- and t-channel processes:

$$M_{fi} = M_{fi}^s + M_{fi}^u + M_{fi}^t . \qquad (2)$$

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In $\gamma p \to \phi p$, M_{fi}^t vanishes since it is protortional to the charge of the final state ϕ meson. Then, with the intermediate states introduced, the s- and u-channel amplitudes can be written as:

$$
\begin{aligned}
M_{fi}^{s+u} & = i\omega_\gamma \sum_j \langle N_f|H_m|N_j\rangle \langle N_j|\frac{1}{E_i + \omega_\gamma - E_j}h_e|N_i\rangle \\
& + i\omega_\gamma \sum_j \langle N_f|h_e \frac{1}{E_i - \omega_\phi - E_j}|N_j\rangle \langle N_j|H_m|N_i\rangle,
\end{aligned}
\tag{3}
$$

with $H_m = -\overline{\psi}(a\gamma_\mu + \frac{ib\sigma_{\mu\nu}q^\nu}{2m_q})\phi_m^\mu \psi$ for the quark-meson coupling vertex, and

$$
h_e = \sum_l e_l \mathbf{r}_l \cdot \boldsymbol{\epsilon}_\gamma(1 - \boldsymbol{\alpha} \cdot \hat{\mathbf{k}})e^{i\mathbf{k}\cdot\mathbf{r}_l}, \ \hat{\mathbf{k}} = \frac{\mathbf{k}}{\omega_\gamma},
\tag{4}
$$

where $\mathbf{k}$ and ω_γ are the three-momentum and energy of the incident photon, respectively. $|N_j\rangle$ represents the complete set of the intermediate states. in the NRCQM, those low-lying states ($n \leq 2$) have been successfully related to the resonances which can be taken into account explicitly in the formula. For those higher excited states, they can be treated degenerate to the main quantum number n in the harmonic oscillator basis. Detailed description of this approach can be found in Ref.[6,7]. In Table 1, resonances in the s-channel with their assignments in the $SU(6) \otimes O(3)$ NRCQM symmetry limit are listed.

Table 1: Resonances in the s-channel with their assignments in the $SU(6) \otimes O(3)$ NRCQM symmetry limit (PDG1998). M_R and Γ_T represent the mass and total width of a resonance, respectively.

Resonances	$SU(6) \otimes O(3)$	M_R (MeV)	Γ_T (MeV)
$S_{11}(1535)$	$N(^2P_M)_{\frac{1}{2}-}$	1535	150
$D_{13}(1520)$	$N(^2P_M)_{\frac{3}{2}-}$	1520	120
$P_{13}(1720)$	$N(^2D_S)_{\frac{3}{2}+}$	1720	150
$F_{15}(1680)$	$N(^2D_S)_{\frac{5}{2}+}$	1680	130
$P_{11}(1440)$	$N(^2S'_S)_{\frac{1}{2}+}$	1440	350
$P_{11}(1710)$	$N(^2S_M)_{\frac{1}{2}+}$	1710	100
$P_{13}(1900)$	$N(^2D_M)_{\frac{3}{2}+}$	1900	400
$F_{15}(2000)$	$N(^2D_M)_{\frac{5}{2}+}$	2000	450

2.2 t-channel diffractive Pomeron exchange

As one has known that the t-channel diffractive process plays dominant role in $\gamma p \to \phi p$. The main feature of the diffractive contribution is that the total cross sections exhibit almost energy-independent which is accounted for by the t-channel Pomeron exchange model by Donnachie and Landshoff based on the Regge phenomenology. In this model, the Pomeron mediates the long range interaction between two confined quarks, and behaves rather like a $C = +1$ isoscalar photon.

We summarize the vertices and form factors as follows:

- Pomeron-nucleon coupling:

$$F_\mu(t) = 3\beta_0 \gamma_\mu f(t), \ \ f(t) = \frac{(4M_N^2 - 2.8t)}{(4M_N^2 - t)(1 - t/0.7)^2} \ .$$ (5)

  where β_0 is the coupling of the Pomeron to one light constituent quark. $f(t)$ is the isoscalar nucleon electromagnetic form factor. The factor 3 comes from the "quark-counting rule".

- Quark-ϕ-meson coupling:

$$V_\nu(p - \frac{1}{2}q, p + \frac{1}{2}q) = f_\phi M_\phi \gamma_\nu \ , \ \ \Gamma_{\phi \to e^+ e^-} = \frac{8\pi \alpha_e^2 e_Q^2}{3}(\frac{f_\phi^2}{M_\phi}) \ .$$ (6)

  where f_ϕ is the decay constant of the ϕ meson in $\phi \to e^+ e^-$, which is determined by the decay width $\Gamma_{\phi \to e^+ e^-}$.

- Form factor for the Pomeron-off-shell-quark vertex:

$$\mu_0^2/(\mu_0^2 + p^2) \ .$$ (7)

  where $\mu_0 = 1.2$ GeV is the cut-off energy scale for the Pomeron-off-shell-quark vertex, and p is the four-momentum of the quark.

- Pomeron trajectory:

$$\alpha(t) = 1 + \epsilon + \alpha't \ , \ \ \alpha' = 0.25 GeV^{-2} \ .$$ (8)

2.3 t-channel π^0 exchange

The π^0 exchange is introduced with the Lagrangian for the πNN coupling and $\phi \pi \gamma$ coupling as the followings:

$$L_{\pi NN} = -ig_{\pi NN} \overline{\psi} \gamma_5 (\boldsymbol{\tau} \cdot \boldsymbol{\pi}) \psi \ .$$ (9)

and

$$L_{\phi\pi^0\gamma} = e_N \frac{g_{\phi\pi\gamma}}{M_\phi} \epsilon_{\alpha\beta\gamma\delta} \partial^\alpha A^\beta \partial^\gamma \phi^\delta \pi^0 \ . \tag{10}$$

Then, the amplitude for the π^0 exchange can be derived in the NRCQM. The commonly used couplings, $g_{\pi NN}^2/4\pi = 14$, $g_{\phi\pi\gamma}^2 = 0.143$, are adopted.

In summary, the parameters appearing in this model are the followings:

- For the t-channel Pomeron exchange terms,

$$\beta_0 = 1.27 \text{GeV}^{-1}$$

is determined by data at $E_\gamma = 6.45$ GeV.

- For the s- and u-channel contribution, numerical fitting of the sparse data (Ref. [11]) gives:

$$a = -0.035 \pm 0.166 \ ; \ b' \equiv b - a = -0.338 \pm 0.075 \ .$$

We hence fix: $|a| = 0.15$, $|b'| = 0.3$ with the reasons: i) The extreme value $|a| = 0.15$ will best show the sensitivity of observables to a; ii) No data available for large angles which might change the phase of b'.

- For the π^0 exchange terms, $\alpha_\pi = 300$ MeV is adopted for the quark potential in which an exponential factor $e^{-\frac{(\mathbf{q}-\mathbf{k})^2}{6\alpha_\pi^2}}$ plays a role as a form factor for the πNN and $\phi\pi\gamma$ vertices. This factor comes out naturally in the harmonic oscillator basis where the nucleon is treated as a non-point-like 3-quark system.

3 Cross sections and the polarization observables

In this work, we limit the discussion to the low energy region near the ϕ meson production threshold, where the effects from nucleon resonances are still expected to play a role. In the $SU(6) \otimes O(3)$ NRCQM symmetry limit, the differential cross section, four single polarization asymmetry observables, and the beam-target double polarization asymmetry are investigated.

In Fig. 1, the differential cross section for $\gamma p \to \phi p$ at $E_\gamma = 2.0$ GeV are shown with different signs for parameters a and b' (full curves). It shows that the Pomeron exchange (dashed curve in Fig. 1(a)) plays dominant role, and accounts for the cross sections at forward angles. The resonances (dotted curves) and the π^0 exchange (dot-dashed curve in Fig. 1(a)) only give small contributions to the cross sections. The heavy-dotted curve in Fig. 1(a) is

the cross sections for $E_\gamma = 6.45$ GeV, where the resonance effects and π^0 exchange are so small that their contributions are negligible. Therefore, the pure Pomeron exchange accounts for the data (diamond), through which the parameter $\beta_0 = 1.27$ for the Pomeron-constituent-quark coupling is determined. With the same β_0, the Pomeron exchange terms are applied to the low energy region, i.e. $E_\gamma = 2.0$ GeV.

In the case of the cross section, since the non-diffractive contributions are so small in comparison of the dominant Pomeron exchange, we do not expect that clear manifestation can be derived for the resonance effects. However, we can see below, that the effects from the small cross sections can be amplified in polarization observables that makes it possible to investigate the role played by the non-diffractive resonance contributions.

The beam polarization asymmetry $\check{\Sigma}$ at $E_\gamma = 2.0$ GeV is shown in Fig. 2. Comparing the Pomeron exchange (dashed curve in Fig. 2(a)) with the Pomeron plus π^0 exchange (dotted curve in Fig. 2(a)), we find that the contribution from π^0 exchange is negligible. The s- and u-channel contributions amplified by the Pomeron exchange, due to the interference terms, increase the magnitude of the asymmetries by about a factor of 3 around $110°$ and produces a sign change above $150°$ (dot-dashed curve in Fig. 2(a)). The three mechanisms together produce the full curves in Fig. 2(a) and (b). We present the results for the four phase sets for parameters a and b' in Fig. 2(b) for comparison.

In Fig. 3, predictions for the target polarization asymmetry $\check{T} \equiv \mathbf{P}_N \cdot \hat{y}\mathcal{T}$, due to the same mechanisms discussed above in the case of the $\check{\Sigma}$ observable are reported. It is worthy noting that the helicity amplitude structure of the $\check{\Sigma}$ observable differs drastically from those of the other single polarization observables. As summarized in the Appendix of Ref. [10], the $\check{\Sigma}$ observable is a bilinear combination of real-real or imaginary-imaginary parts of the helicity elements, while the other three single polarization observables depend on real-imaginary couples. As the Pomeron exchange amplitude is treated purely imaginary in this model, the pure Pomeron exchange leads to a zero asymmetry (dashed curve in Fig. 3(a)) for the target polarization observable. The π^0 exchange is purely real. Therefore, when the π^0 exchange is added, the interference between the Pomeron exchange and the π^0 exchange produces non-zero effects (dotted curve in Fig. 3(a)). The Pomeron plus resonances contributions (dot-dashed curve in Fig. 3(a)) gives even a larger asymmetry in magnitude than the Pomeron plus π^0 exchange does. The full calculation (full curves in Fig. 3(a) and (b)) shows a minimum around $20°$ due to π^0 exchange and a maximum around $130°$ generated by the resonance terms. In both cases the Pomeron exchange plays an amplifying role in the predicted asymmetries.

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It shows that the target polarization asymmetry is governed mainly by the resonance contributions at large angles. For comparison, we also present the results with phase changes in Fig. 3(b).

In the target polarization observable, we find that a large cancellation arises between the longitudinal and transverse parts of the asymmetry, which produces a nearly zero asymmetry at $\sim 65°$. This structure is independent on the relative phase between the Pomeron exchange and the π^0 exchange amplitudes, since the Pomeron exchange amplitude is purely imaginary and the π^0 exchange is purely real, therefore, the phase change will only give an overall sign to the dotted curve in Fig. 3(a).

The vector meson polarization and the recoil polarization observables are shown in Fig. 4 and Fig. 5, respectively.

In the single polarization observables, the Pomeron exchange mechanism turns out to be an efficient amplifier for the non-diffractive mechanisms suppressed in the cross sections. Although the influence of the π^0 exchange can be amplified in some polarization observables, it plays in general a rather minor role. Therefore, this might imply that the double-counting from duality (if it exits) is negligible. The nodal structure of the observables depends (in some cases strongly) on the signs of the two couplings a and b'. At large angles, it is the interferences from the s- and u-channel resonances that produce significant asymmetries.

Given the availability of polarized beam and polarized target, we now concentrate on the beam-target (BT) double polarization asymmetry. Another motivation in investigating this observable is that a recently developed strangeness knock-out model [9] suggests that a small $s\bar{s}$ component ($\sim 5\%$) in the proton might result in large asymmetries ($\sim 25\text{-}45\%$) in the BT observable at small angles. However, since the resonance contributions have not been taken into account there, an interesting question is: if contributions from the s- and u-channel can produce a significant double polarization asymmetry without introducing strangeness component or not.

Our predictions are shown in Fig. 6. The Pomeron exchange alone (dashed curve in (a)), gives a small negative asymmetry at forward angles. But at large angles, the asymmetry goes to about -0.4. The inclusion of π^0 exchange (dotted curve in (a)) does not change the asymmetry significantly. However, we find that the resonances contributions have quite strong interference with the Pomeron exchange terms (dot-dashed curve in (a)). The full calculation leads finally to a decreasing behavior, going from almost zero at forward angles to ~ -0.7 at $180°$. This result (full curve in Fig. 6(a) and (b)) is obtained with $a = -0.15$ and $b' = +0.3$. The backward angle effects are also large in the case of $a = +0.15$ and $b' = -0.3$ (dot-dashed curve in Fig. 6(b)). The

situation becomes very different for the couplings sets with the same signs: the effect is suppressed for $a = +0.15$ and $b' = +0.3$ (dotted curve in Fig. 6(b)), and the shape changes drastically for $a = -0.15$ and $b' = -0.3$ (dashed curve in Fig. 6(b)). The latter set produces (almost) vanishing values at extremely backward angles. However, the common feature of the four sets is that at forward angles, only small BT asymmetries are produced by the s- and u-channel resonance excitations though such an interference produces dramatic changes at large angles. This result makes it interesting that at forward angles, large asymmetries in the BT observable might be able to provide some hints for other non-diffractive sources, especially, the possible strangeness contents in nucleons.

4   Discussion and Conclusion

In the above sections, the calculations of the nucleonic resonance effects have been done in the $SU(6) \otimes O(3)$ symmetry limit. However, at the energy of the ϕ meson production threshold, the NRCQM symmetry is not a good approximation any more, and large configuration mixings are expected. Thus, one question which must be answered in the intestigation of the role of the intermediate resonances is that, "what are the effects produced by the configuration mixings?" Meanwhile, concerning the Pomeron exchange terms, which plays a role of amplifying, another question that one has to answer is, "what are the effects from different Pomeron exchange amplitudes due to different gauge fixing schemes?" These two aspects have been taken into account in our submitted work, and we refer the readers to Ref. [10] for detailed discussions. Here, we just summarize the main points because of the limited page space.

1. **Pomeron gauge invariance effects**:

    In the Pomeron exchange model, one meets the problem of fixing the gauge for the quark loop tenser. Therefore, several schemes are introduced. With the pure Pomeron exchange, these schemes are consistent with each other at small angles. However, they behave differently at large angles. Therefore, the polarization asymmetries, which come from the interferences between the diffractive Pomeron exchange terms and the non-diffractive amplitudes, might depend on the gauge fixing schemes, and make the predictions trivial, especially at large angles. However, with the non-diffractive contributions taken into account, we find that the polarization observables investigated are not sensitive to the Pomeron structures, i.e. the asymmetries exhibit consistent behaviors even when different gauge fixing schemes are employed, and have little dependence

on the Pomeron exchange model not only at small angles, but also at large angles.

2. **Configuration mixing effects**:

The present data for $\gamma p \to \phi p$ near threshold are too scarce to allow a study of possible deviations from the $SU(6) \otimes O(3)$ symmetry. As we discussed in Ref.[10], a reasonable alternative is to derive the configuration mixing coefficients for $\gamma p \to \phi p$ with an analogy to $\gamma p \to \omega p$ of which recent data from SAPHIR[13] can provide a first glance at the possible configuration mixings. In $\gamma p \to \omega p$, for each resonance, C_R is introduced for the amplitude, i.e. $h^J_{a\lambda_V} \to C_R\, h^J_{a\lambda_V}$, where $C_R \neq 1$ means the deviation from the $SU(6) \otimes O(3)$ symmetry. Then, the derived C_R is used in $\gamma p \to \phi p$ to investigate the configuration mixing effects in the polarization observables. We find that the configuration mixings only produce small asymmetries at small angles though at large angles, the mixings can change the asymmetries significantly.

In summary, in the ϕ meson photoproduction near threshold, we find that some polarization observables are not sensitive to resonance conrtibutions at forward angles though the asymmetries from the resonance interferences become significant at large angles. Therefore, at forward angles, the insensitivities of polarization observables to the s- and u-channel non-diffractive process imply that observations at small angles might be able to pin down the asymmetries from other channels, e.g. small strangeness component in nucleons. At large angles, the significant sensitivities might provide insight to the non-diffractive ϕ meson production mechanism.

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Figure captions

- Fig. 1. Differential cross sections for $\gamma p \to \phi p$. Data at $E_\gamma = 2.0$ GeV (full circle) come from Ref.[11], and at $E_\gamma = 6.45$ GeV (diamond) from Ref.[12]. The heavy dotted curve in (a) is the Pomeron exchange at $E_\gamma = 6.45$ GeV, while all the other curves are produced at $E_\gamma = 2.0$ GeV. The curves are: i) π^0-exchange (dot-dashed); ii) s- and u-channel contribution (dotted); iii) Pomeron exchange(dashed), and iv) contributions from i) to iii) (full curves).

- Fig. 2. The polarized beam asymmetry at $E_\gamma =2.0$ GeV with different phase signs. The curves in (a) stand for: Pomeron exchange (dashed), Pomeron and π^0 exchanges (dotted), Pomeron exchange and resonance contributions (dot-dashed), and the full calculation including all three components with $a = -0.15$, $b' = 0.3$ (full). In (b), the results of the full calculations for the four (a, b') sets are depicted.

- Fig. 3. Same as Fig. 2, but for the polarized target asymmetry.

- Fig. 4. Same as Fig. 2, but for the polarized vector meson asymmetry.

- Fig. 5. Same as Fig. 2, but for the recoil polarization asymmetry.

- Fig. 6. Same as Fig. 2, but for the beam-target double polarization asymmetry.

Beam Asymmetry (y-axis)

(a) a = − 0.15
b′ = + 0.3

(b)
——— (-, +)
- - - (-, -)
.... (+, +)
·—·— (+, -)

θ

Target Asymmetry (y-axis)

(a) $a = -0.15$
$b' = +0.3$

(b)

— $(-, +)$
-- $(-, -)$
.... $(+, +)$
.—.— $(+, -)$

θ

(a) $a = -0.15$
$b' = +0.3$

(b)
—— $(-, +)$
- - $(-, -)$
.... $(+, +)$
._._ $(+, -)$

Vector Meson Asymmetry

θ

Recoil Polar. Asymmetry (y-axis)

(a) a = − 0.15
b′ = + 0.3

(b) —— (−, +)
- - (−, −)
···· (+, +)
·_·_ (+, −)

θ